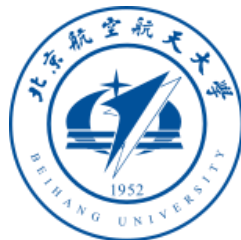


UI-CTX: Understanding UI Behaviors with Code Contexts for Mobile Applications

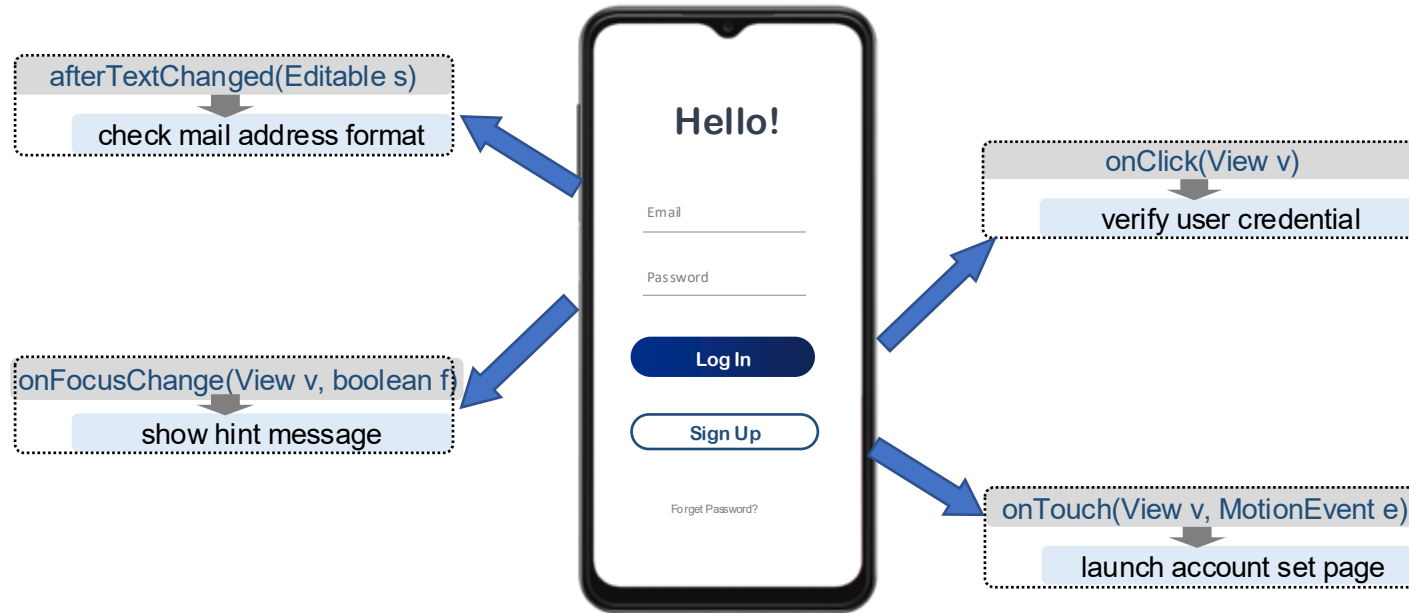
*Jiawei Li**, *Jiahao Liu**, *Jian Mao*, *Jun Zeng*, *Zhenkai Liang*

NDSS, February 2025



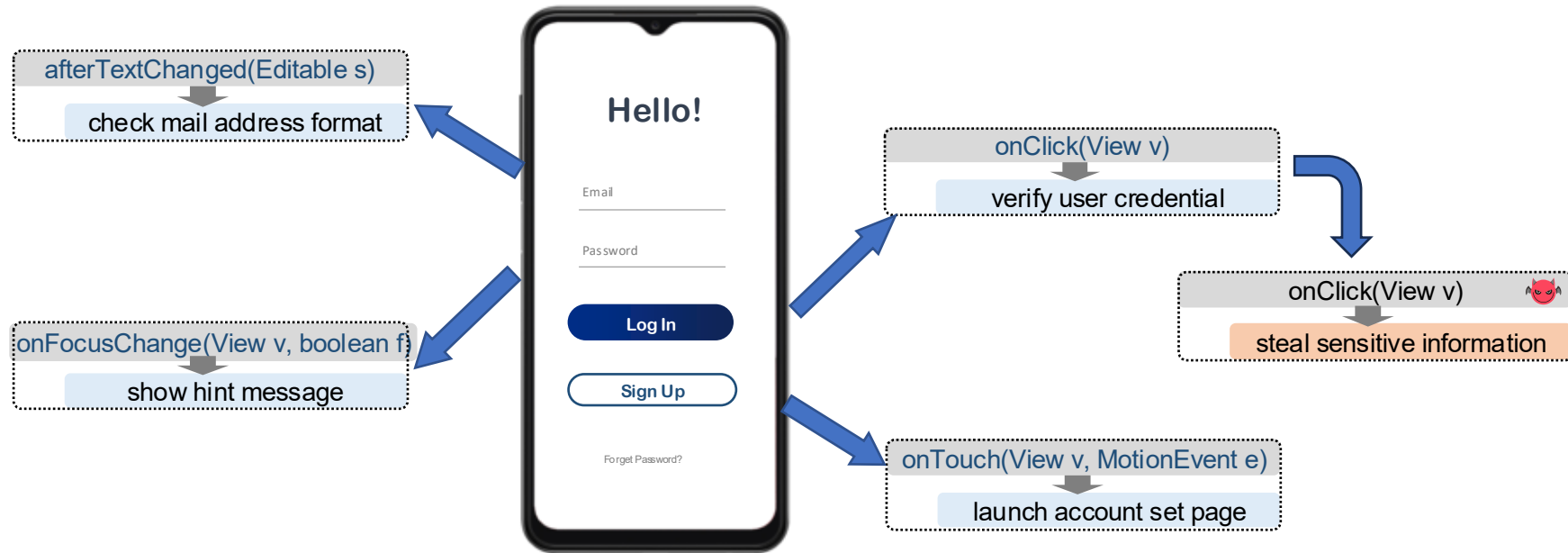
UI Behaviors in Mobile Applications

Mobile apps utilize UI widgets to interact with users and trigger specific operational functionalities



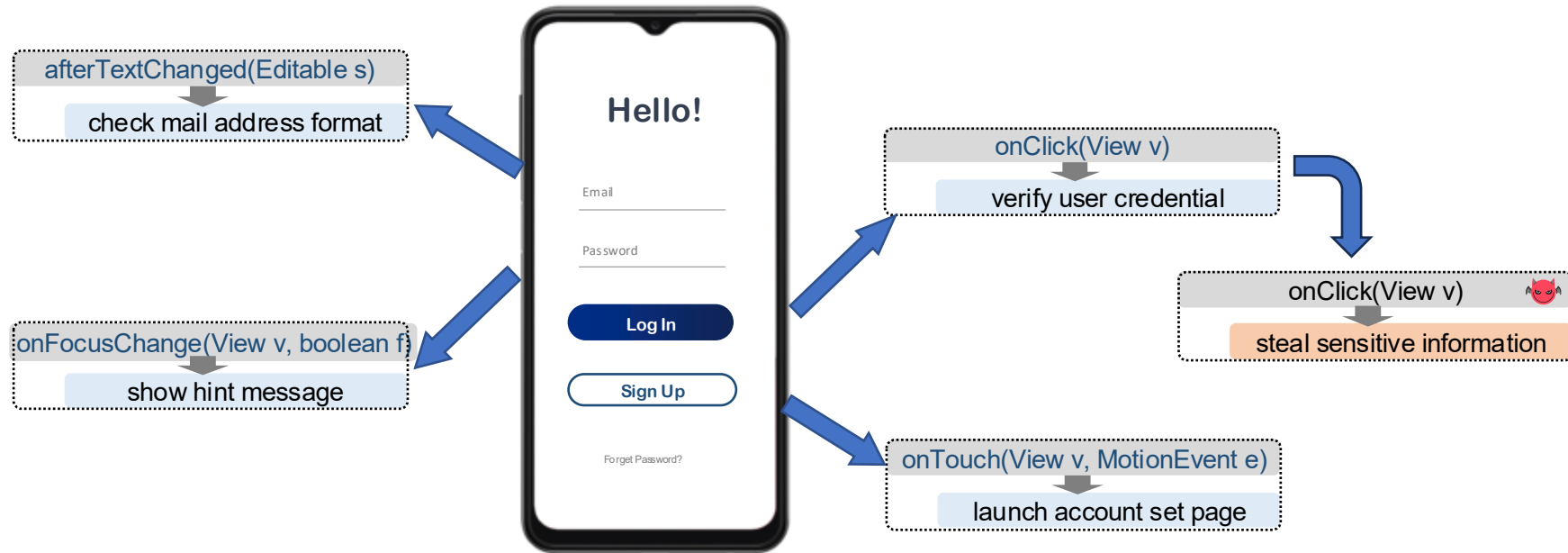
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UI Behaviors in Mobile Applications

Mobile apps utilize UI widgets to interact with users and trigger specific operational functionalities




It is important to identify and understand the *intended behaviors* behind UI widgets to mitigate such potential threats

Representing UI Widgets Behaviors

Representing UI widgets' behaviors generally fall into three categories: appearance-based, permission-based, and code-based methods

- **Appearance-based**

- Image or text on UI widgets
- fail to recognize the real intended behaviors

"LOGIN"  appearance

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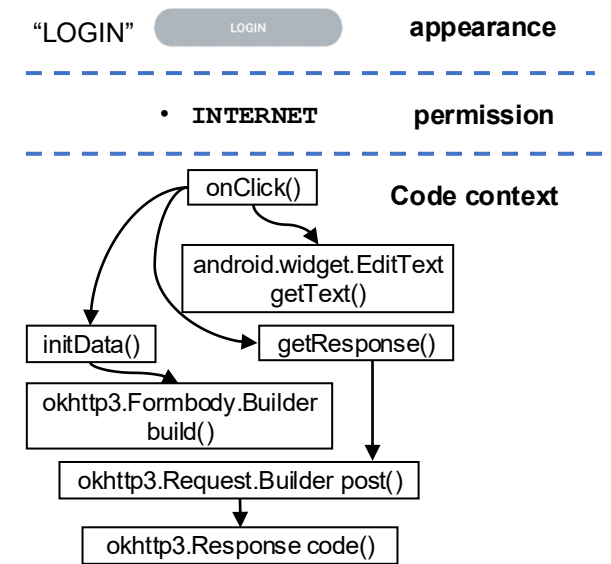
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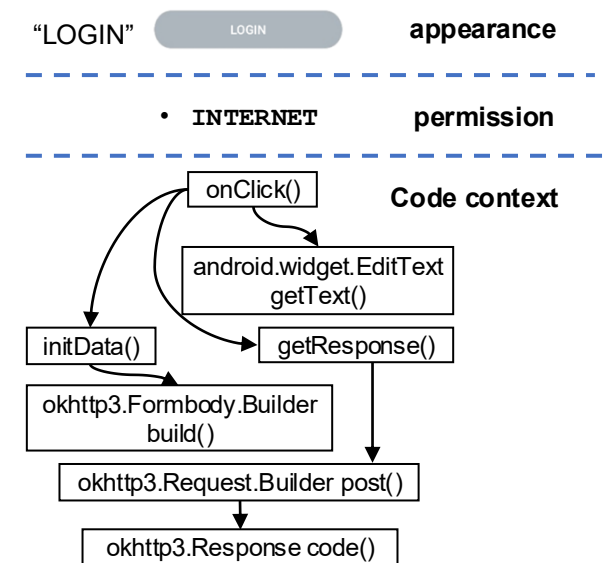
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- **Code-based**

- Code contexts behind UI widgets include details describing widget behaviors



Code contexts contain essential information and can serve as the basis for describing UI intended behaviors

Challenges

A Over-estimated widget and code context pairs

Analyze variable reachability to link widgets with code (e.g., \$r6 flows to all events)

```
1 // app: com.mediaaz.bryanadamtopfree
2 $r6 = invoke $r1.<findViewById(int)>(2131230766)
3 $r11 = (ImageView) $r6
4 $r6 = invoke $r1.<findViewById(int)>(2131230767)
5 $r12 = (ImageView) $r6
6 $r6 = invoke $r1.<findViewById(int)>(2131230768)
7 $r13 = (ImageView) $r6
8 ...
9 $r25 = new Gallery$Adapter$7
10 invoke $r25.<Gallery$Adapter$7: void <init>(...)
11 invoke $r11.<void setOnClickListener(...)>($r25)

12 $r26 = new Gallery$Adapter$8
13 invoke $r26.<Gallery$Adapter$8: void <init>(...)
14 invoke $r12.<void setOnClickListener(...)>($r26)

15 $r27 = new Gallery$Adapter$9
16 invoke $r27.<Gallery$Adapter$9: void <init>(...)
17 invoke $r13.<void setOnClickListener(...)>($r27)
```

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16 invoke $r27.<Gallery$Adapter$9: void <init>(...)
17 invoke $r13.<void setOnClickListener(...)>($r27)
```

Not all code in the “right” event callback can be triggered at app runtime

```
1 // app: com.bionicpanda.aquapets
2 r0 := @this: TankWallActivity
3 $r1 := @parameter0: View
4 $i0 = invoke $r1.<View: int getId()>()
5 lookupswitch($i0) {
6   case 2131427367: goto s1;
7   case 2131427707: goto s2;
8   case 2131427708: goto s3;
9   case 2131427713: goto s4;
10  default: goto return;
11 }
12 return
13 s2: invoke r0.<TankWallActivity: void finish()>()
14 return
15 s1: invoke <game.b: void a(int)>(0)
16 invoke r0.<TankWallActivity: void a(int)>(99)
17 return
18 s3: $r2 = new Intent
19 $r3 = invoke r0.<TankWallActivity: Context
    getApplicationContext()>()
20 ...
21 return
22 s4: $r4 = r0.<TankWallActivity: EditText e>
23 $r5 = invoke $r4.<EditText: Editable getText()>()
```

Challenges

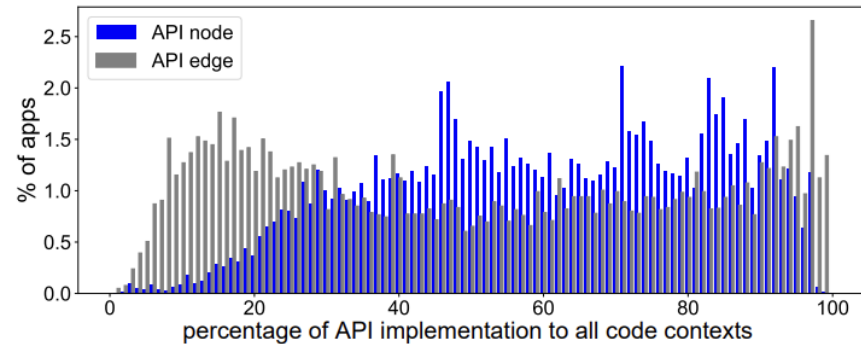
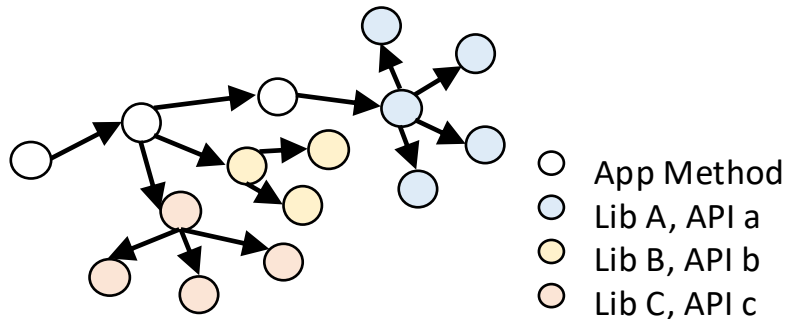
B Extensive unnecessary code contexts

Apps often rely on third-party library (TPL) and software development kit (SDK) APIs (*e.g.*, HTTP requests) to implement their functionalities

Challenges

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Apps often rely on third-party library (TPL) and software development kit (SDK) APIs (e.g., HTTP requests) to implement their functionalities

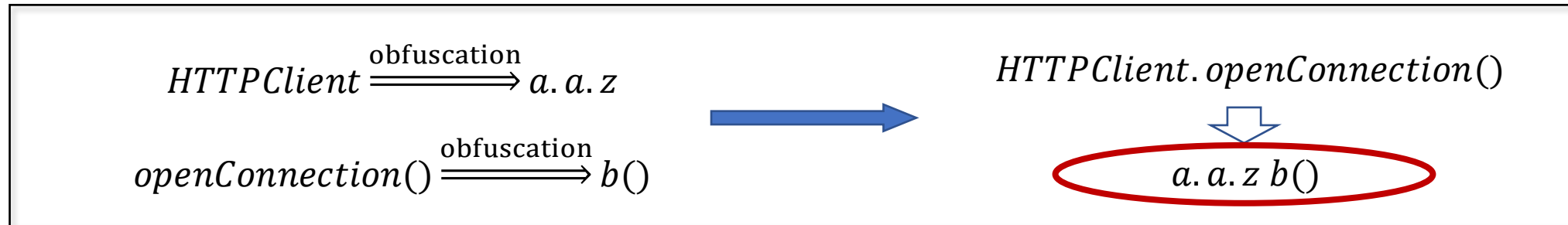


- In **88% of apps**, **>30%** of function calls originate from external TPL/SDK APIs
- In **over half of apps**, external APIs make up **>60% of the app code** *Based on 20,000 apps

Challenges

C Limited function call semantics

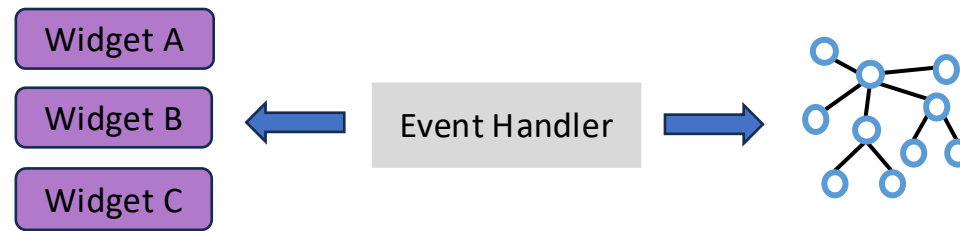
- Class and function names are commonly used to represent a function's semantics since they reasonably reflect its purpose
- Code shrinking and protection techniques obfuscate name semantics



Limited meaningful code semantics

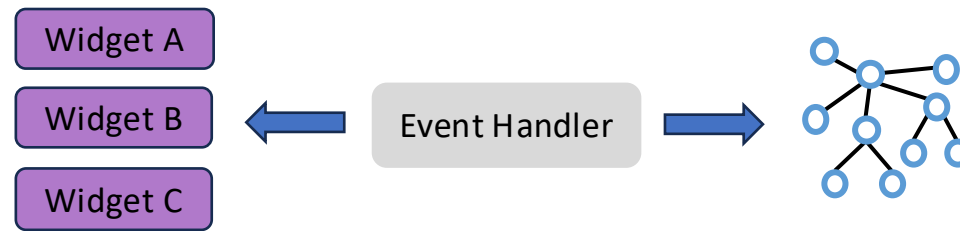
Our Insights

- Begin with the event handler to explore widget-code pairs



Our Insights

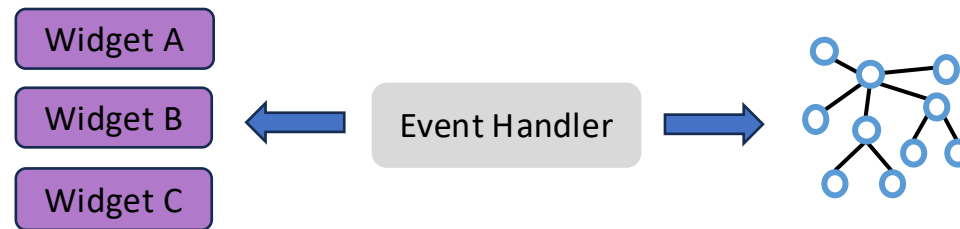
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- Abstract and summarize external libraries to reduce unnecessary code, allowing a focused analysis of widget behaviors

Our Insights

- Begin with the event handler to explore widget-code pairs



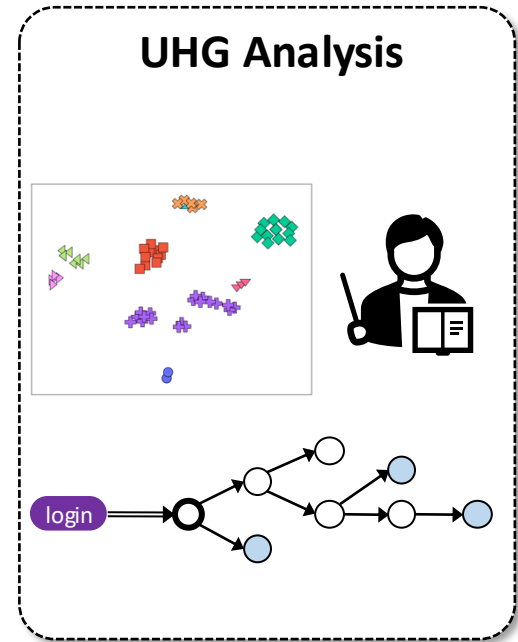
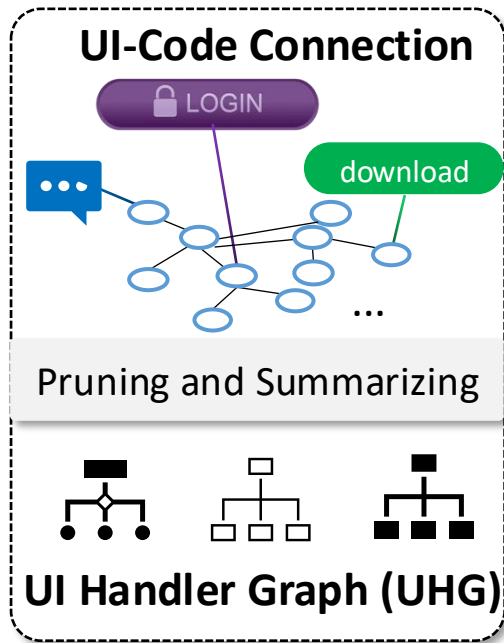
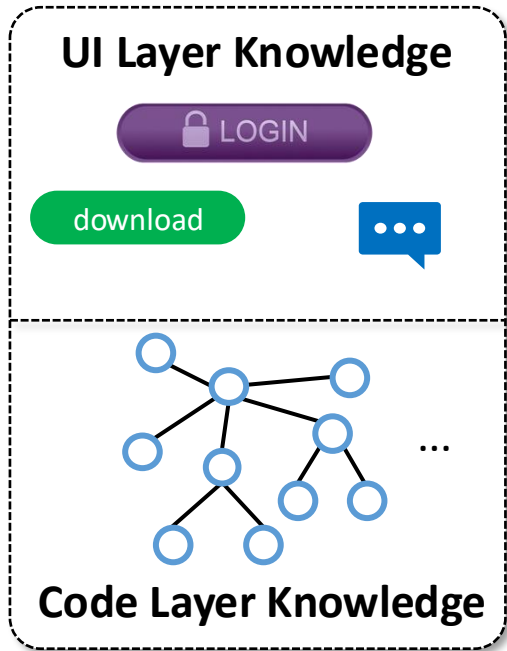
- Abstract and summarize external libraries to reduce unnecessary code, allowing a focused analysis of widget behaviors
- Instruction opcodes serve as the fundamental units of functions, providing stability and robustness

UI-CTX Overview

Knowledge Extraction

UHG Construction

Behavior Investigation



Knowledge Extraction

 *Leverage both UI and code layer knowledge to build UHG*

Knowledge Extraction

 **Leverage both UI and code layer knowledge to build UHG**

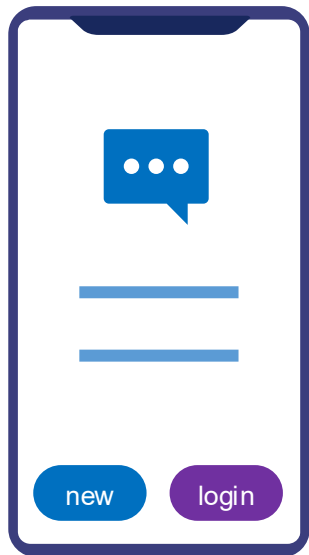
UI Layer Semantics

Layout Id

Widget Id

Text

Image



Layout id
0x7f0500c5

layout/activity_login

ImageView

src: "Logo"

id: 2131493103

Button

id: 2131493104

Button

text: "login"

id: 2131493105

...

Knowledge Extraction

💡 **Leverage both UI and code layer knowledge to build UHG**

UI Layer Semantics

Layout Id

Widget Id

Text

Image



Layout id
0x7f0500c5

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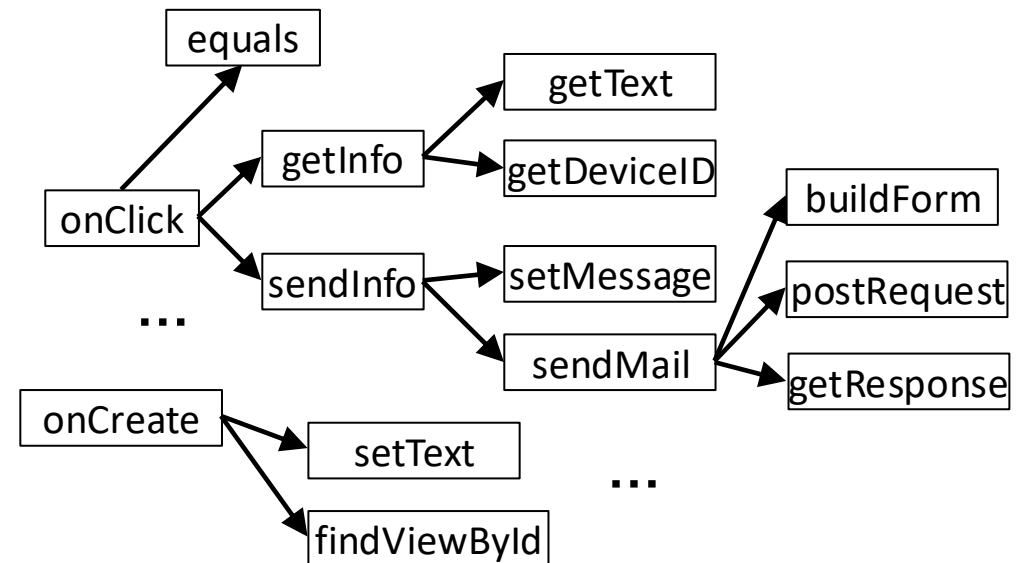
...

Code Layer Semantics

Event

Method Implement

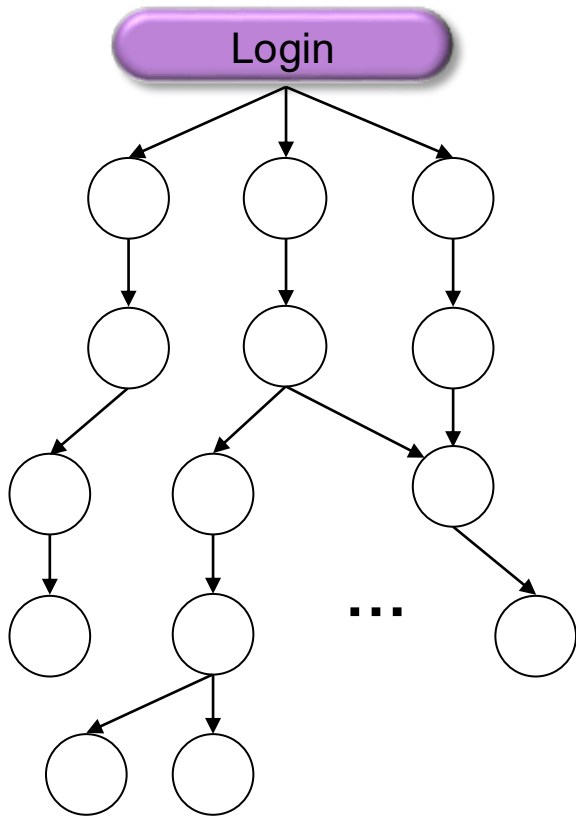
Code Block



UHG Construction



Make the representation precise and concise



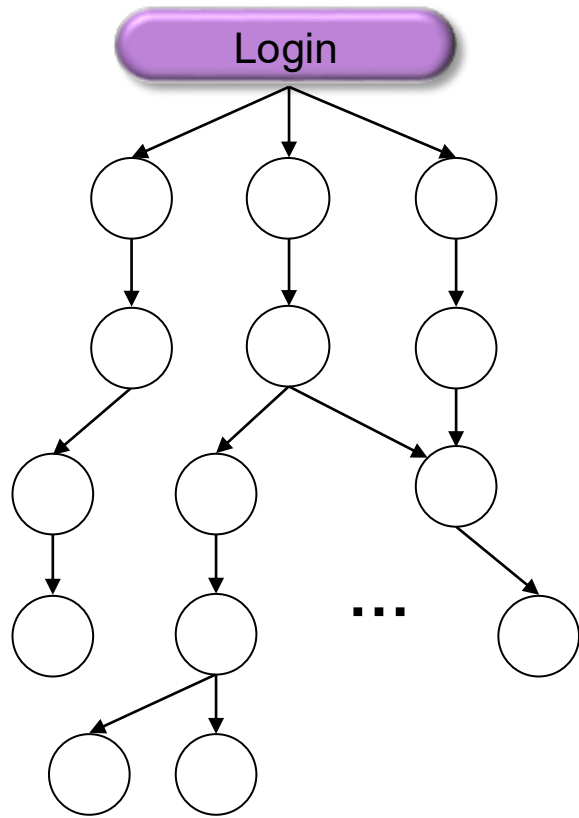
Event Set

```
public class MainActivity extends Activity {
    private android.widget.Button btnLogin;
    private static final String BTN_TEXT;
    public void onCreate() {
        MainActivity r0;
        r0 := <MainActivity: String BTN_TEXT>
        invoke r0.<Activity: void setContentView(int)>(ID_X);
        r0 := @this: MainActivity;
        $r1 = invoke r0.<Activity: View findViewById(int)>(ID_Y);
        $r2 = (android.widget.Button) $r1
        r0.<MainActivity: Button btnLogin> = $r2;
        View$OnClickListener $r1;
        r0 := @this: MainActivity;
        $r1 = new MainActivity$1;
        invoke $r1.<MainActivity$1: void <init>(...);
        $r2 = r0.<MainActivity: Button btnLogin>;
        invoke $r2.<void setOnClickListener...>($r1);
        return;
    } ... }
```

UHG Construction



Make the representation precise and concise



Backward
Tracking

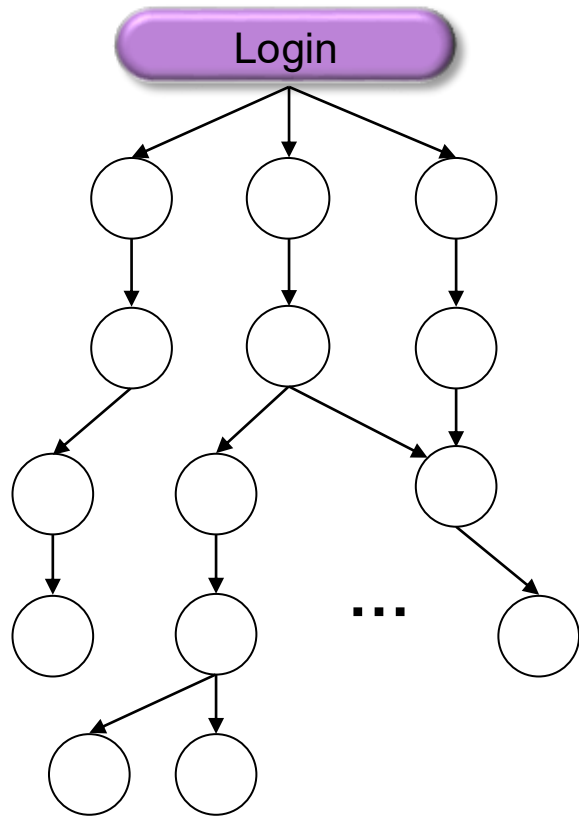
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        $r2 = (android.widget.Button) $r1
        r0.<MainActivity: Button btnLogin> = $r2;
        View$OnClickListener $r1;
        r0 := @this: MainActivity;    <---, MainActivity$1.onClick()>
        $r1 = new MainActivity$1;
        invoke $r1.<MainActivity$1: void <init>(...)>;
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UHG Construction



Make the representation precise and concise



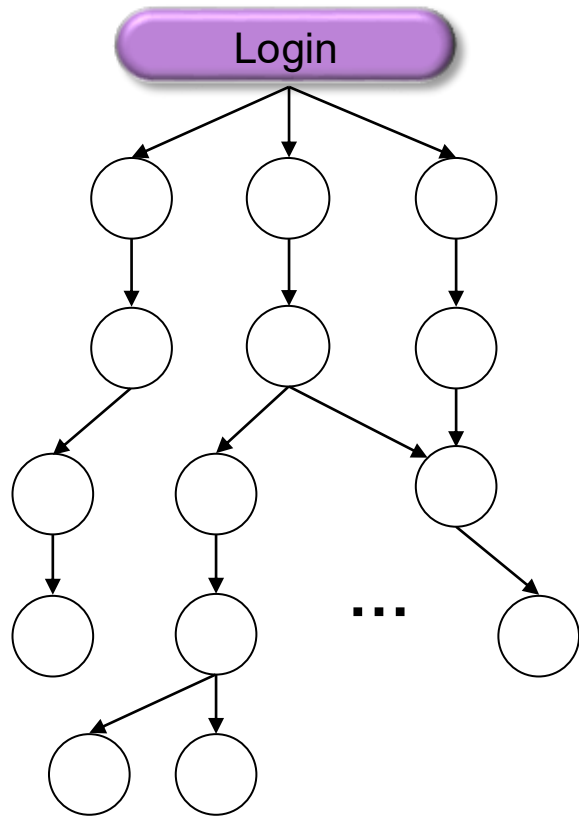
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UHG Construction

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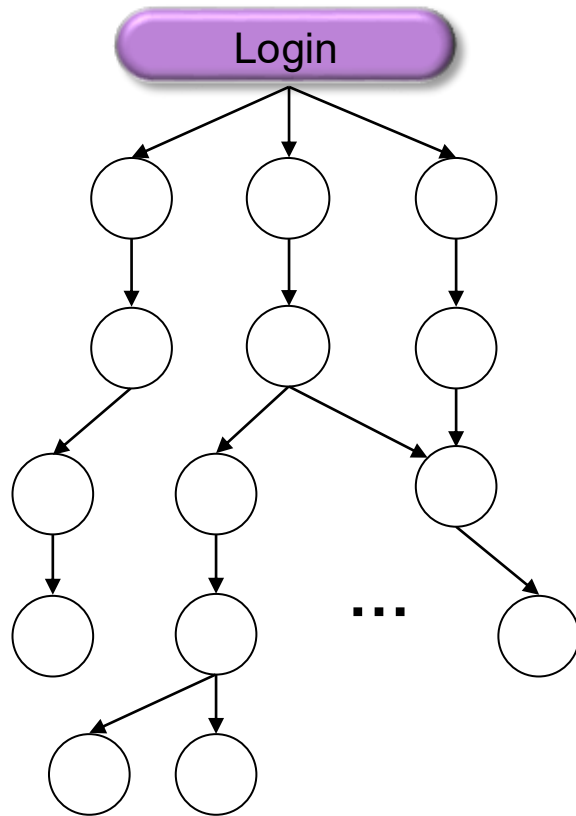
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UHG Construction



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Widget Id

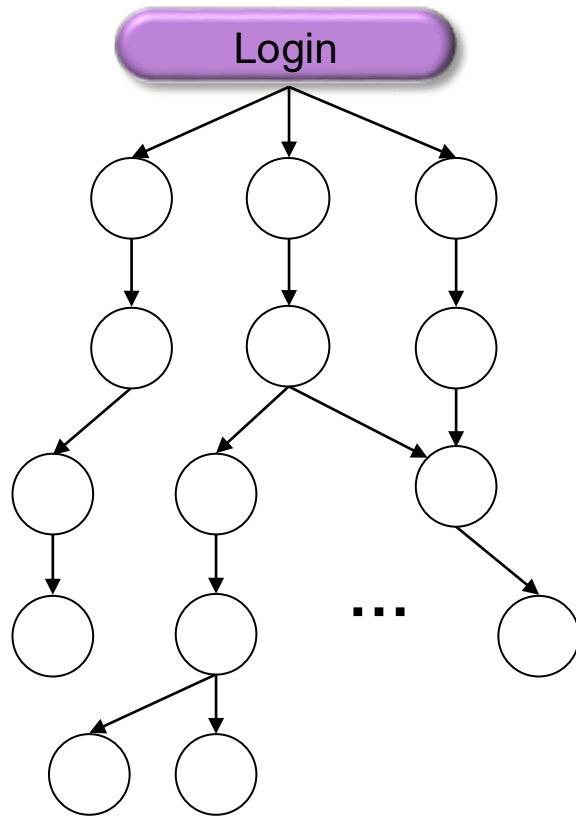
Backward
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Make the representation precise and concise



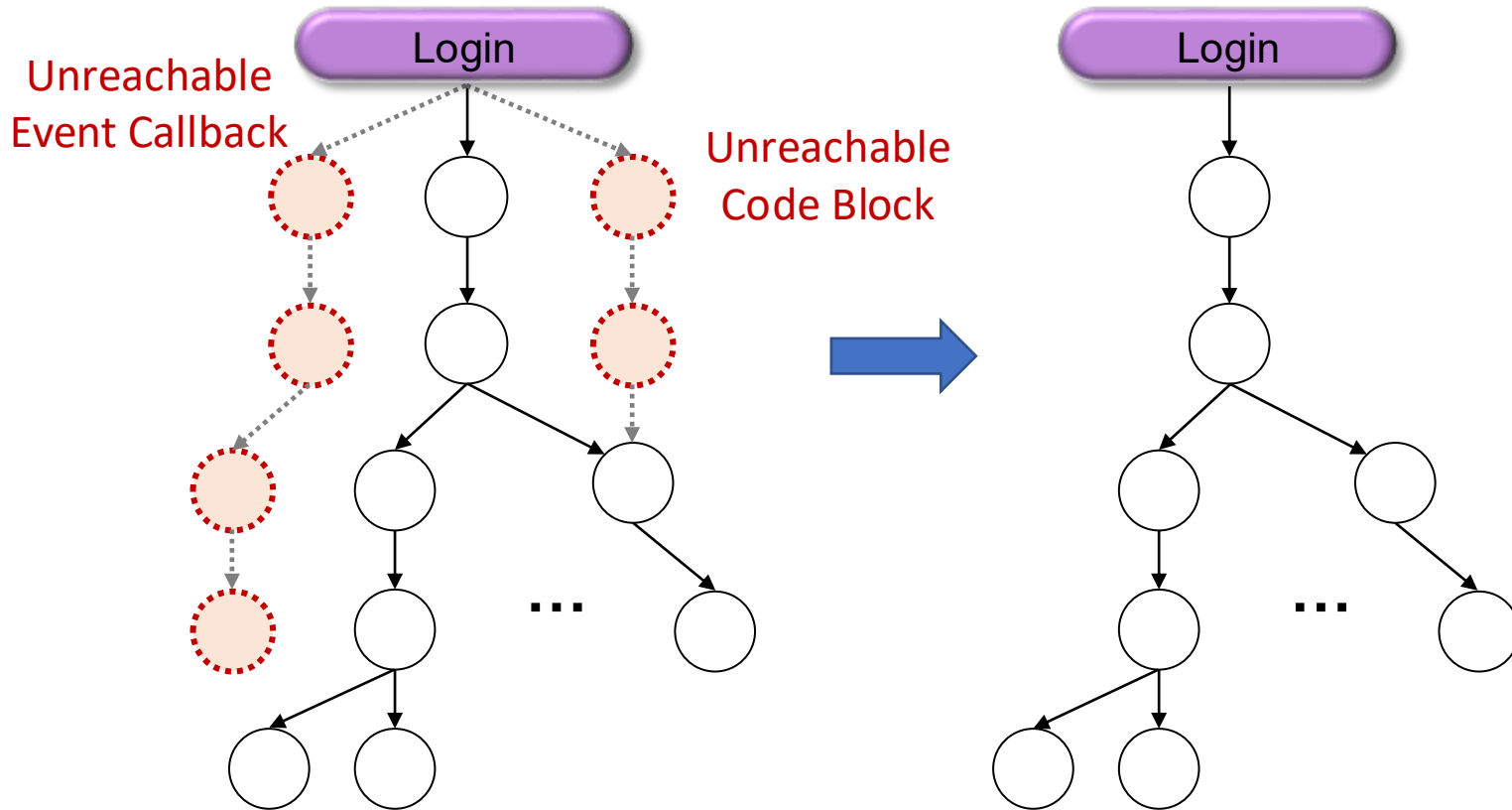
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    default: goto return;
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    return
s4: $r4 = r0.<TankWallActivity: EditText e>
    $r5 = invoke $r4.<EditText: Editable getText()>()
```

Code Block for
Id: 2131427367

UHG Construction



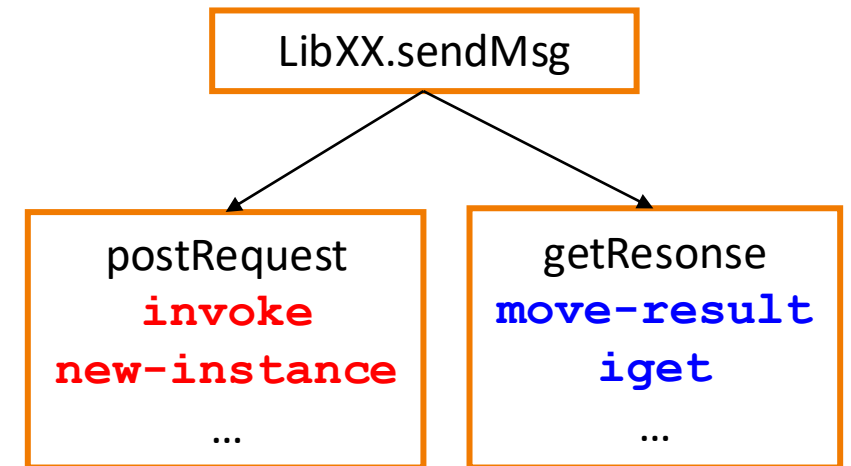
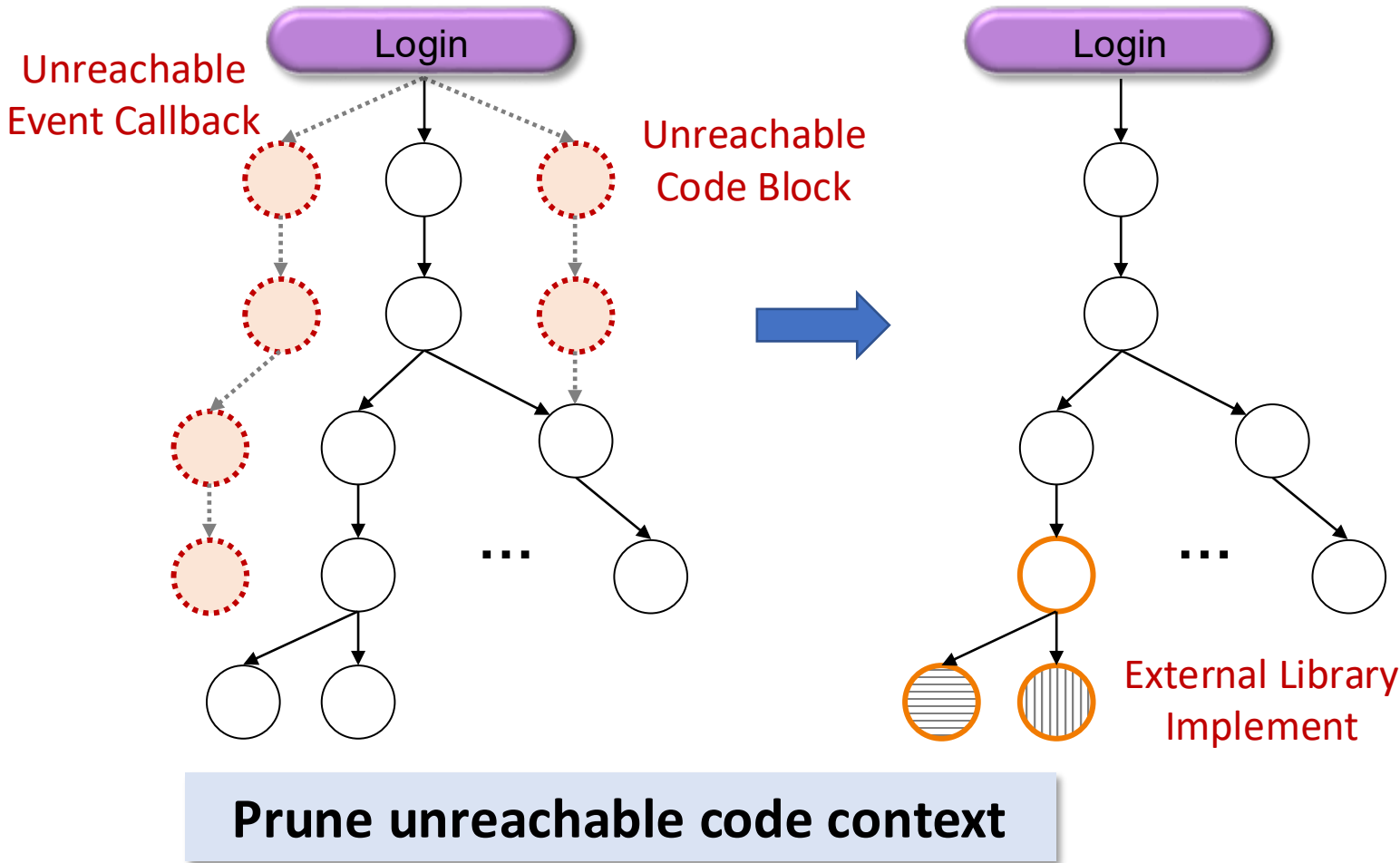
Make the representation precise and concise



UHG Construction



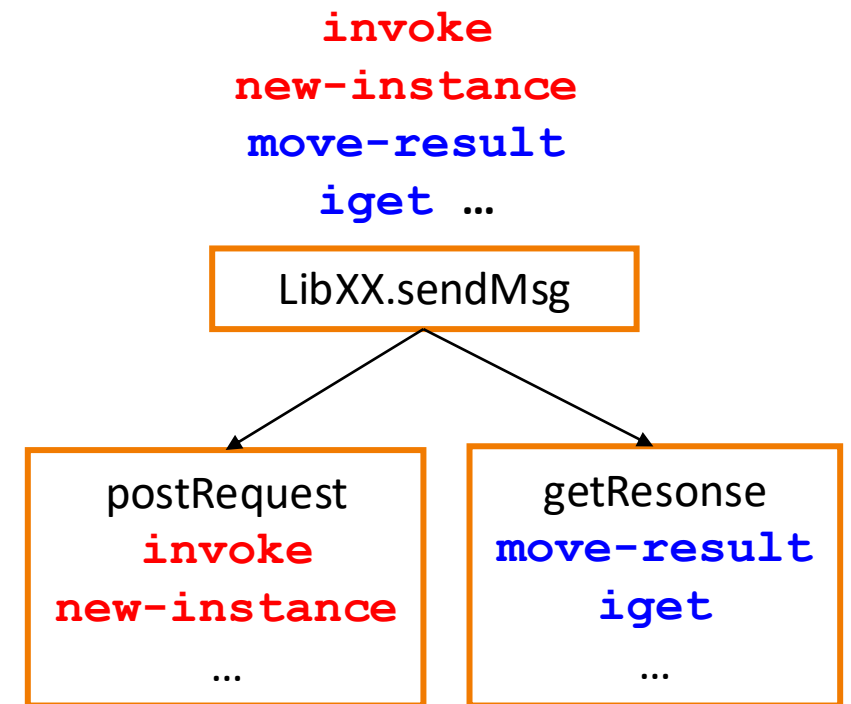
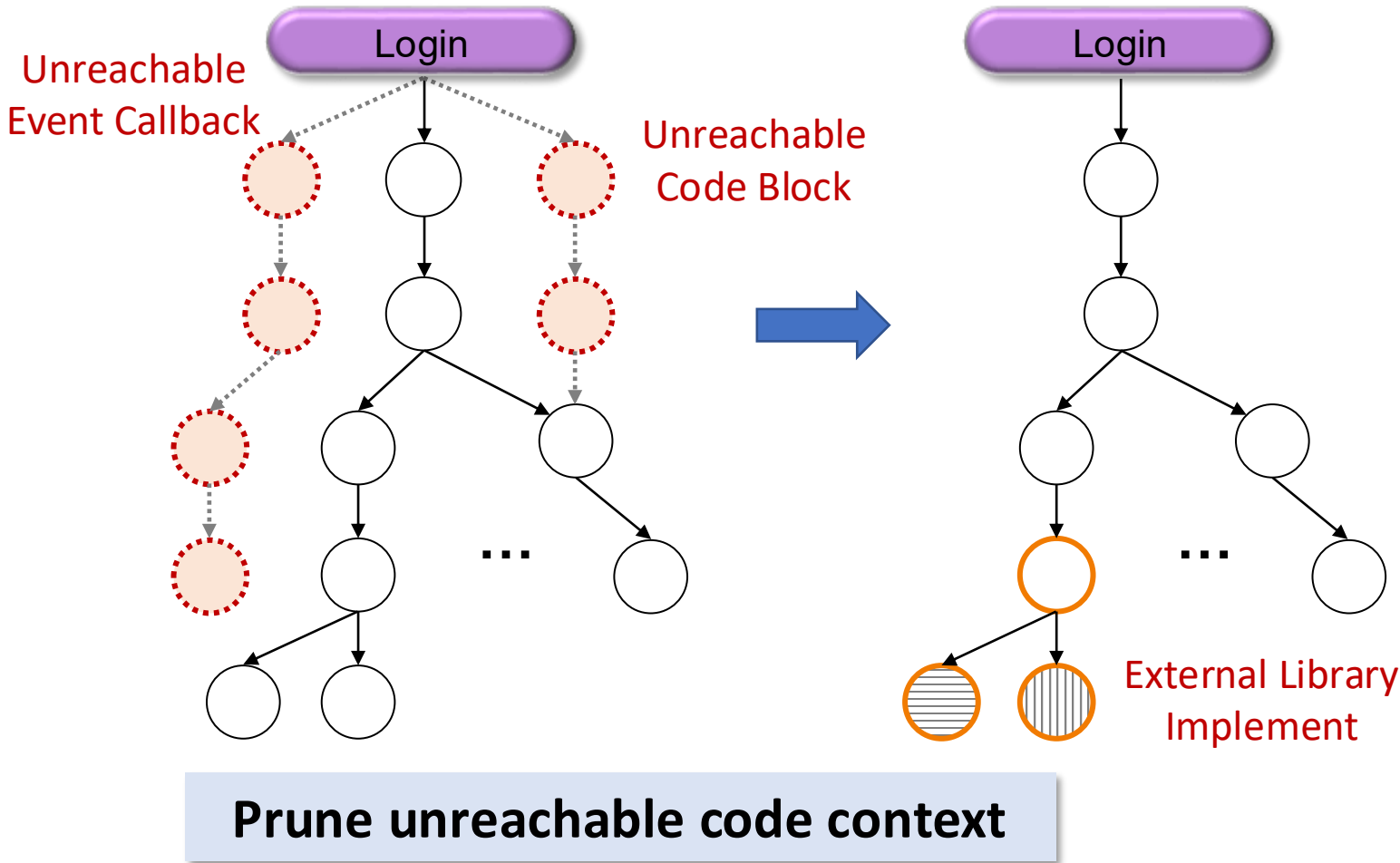
Make the representation precise and concise



UHG Construction



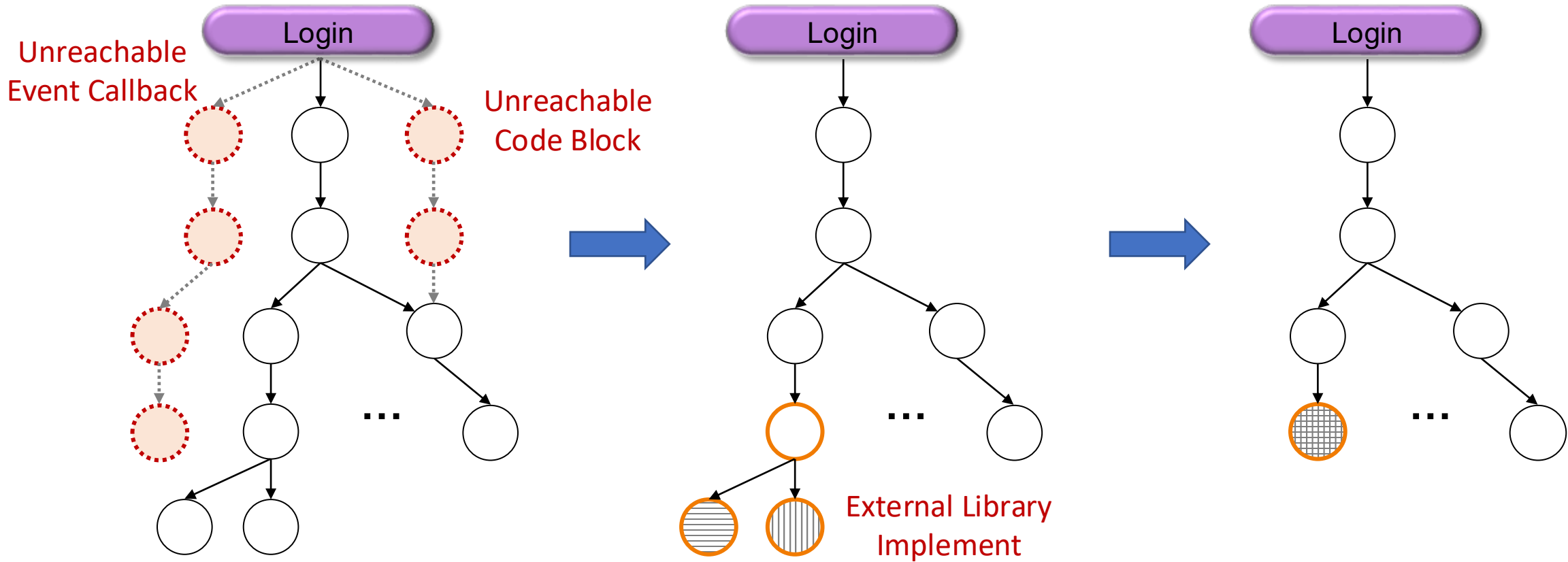
Make the representation precise and concise



UHG Construction



Make the representation precise and concise



Prune unreachable code context

Summarize extensive code information

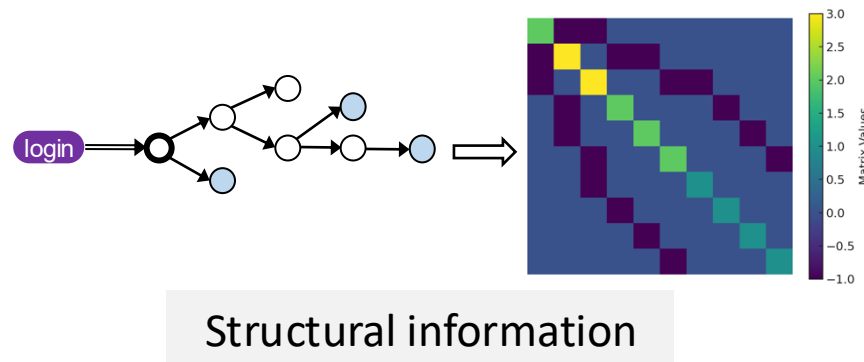
Behavior Investigation

 *Distill both structural and node features into a meaningful and informative representation*

Behavior Investigation

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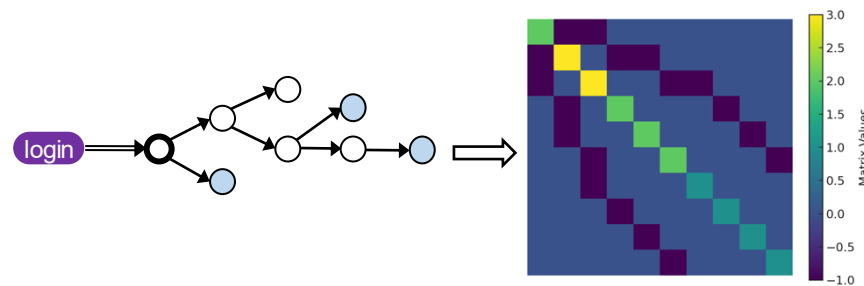
- Eigenvalues of graph Laplacian matrix capture the **global structural information** (community structure and connectivity pattern)



Behavior Investigation

💡 *Distill both structural and node features into a meaningful and informative representation*

- Eigenvalues of graph Laplacian matrix capture the **global structural information** (community structure and connectivity pattern)
- Opcodes capture **instruction-level** node features



Structural information

```
INVOKE_DIRECT
NEW_INSTANCE
CONST_STRING
IF_EQZ
SGET_BYTE
ADD_INT_LIT16
```

$\mu(X)$ Average pooling:
the central tendency

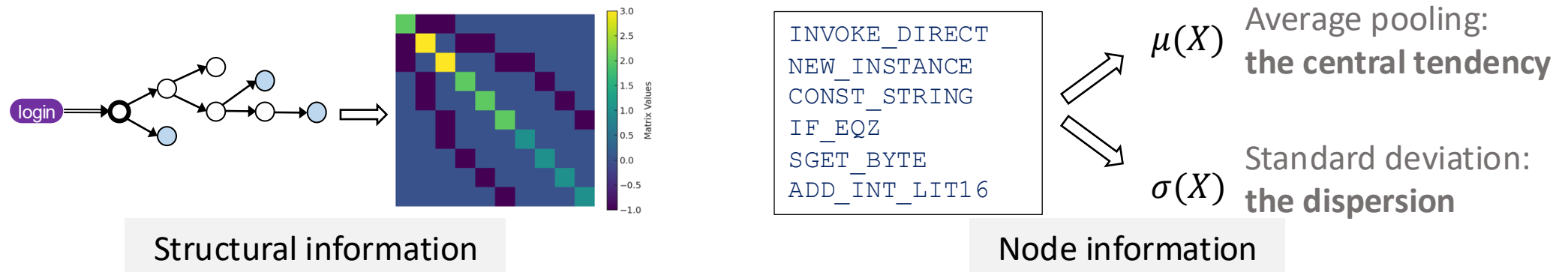
$\sigma(X)$ Standard deviation:
the dispersion

Node information

Behavior Investigation

💡 *Distill both structural and node features into a meaningful and informative representation*

- Eigenvalues of graph Laplacian matrix capture the **global structural information** (community structure and connectivity pattern)
- Opcodes capture **instruction-level** node features



- Group UI widgets with similar functionalities based on UHG

Evaluation

Evaluation Setup

- Collect 40,000 Android apps from AndroZoo
 - Spanning 10 years (4000 per year)
 - Various market sources (Google Play, VirusShare, Mi, and Anzhi)
 - UI widgets related to account management / data operation

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Evaluation Aspects

- How UHG performs in widget behavior description compared to existing representations?
- To what extent do the different design choices in UI-CTX contribute to its performance?
- Can UI-CTX facilitate real-world app analysis?

Effectiveness of Describing UI Widget Behaviors

- Compare UI Handler Graph (UHG) with other representations (F1-score)
 - Baselines: Permission set, Call sequence

Category	delete	login	logout	send	search	download	share	save
Permission	0.29	0.36	0.37	0.60	0.31	0.47	0.81	0.38
Sequence	0.65	0.72	0.97	0.68	0.63	0.76	0.91	0.63
UHG	0.69	0.78	0.98	0.72	0.73	0.86	0.93	0.71

Effectiveness of Describing UI Widget Behaviors

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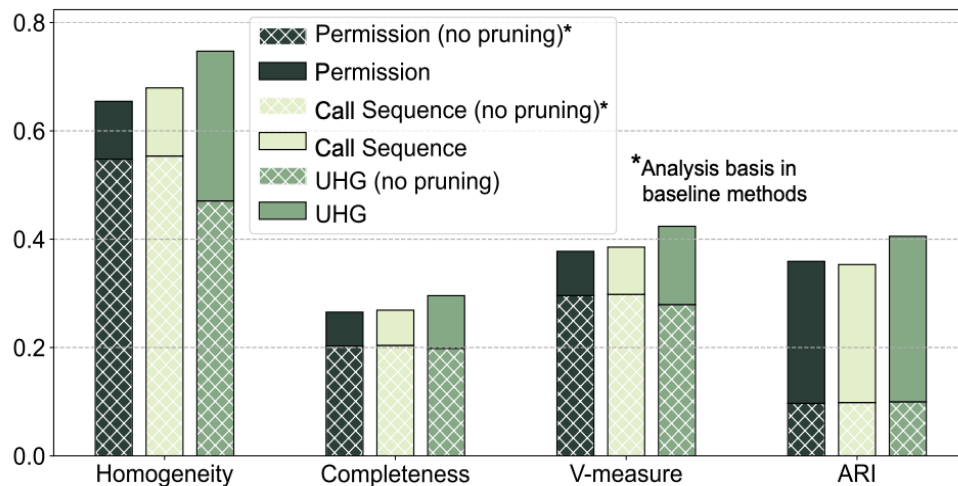
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UHG	0.69	0.78	0.98	0.72	0.73	0.86	0.93	0.71

UI Handler Graph (UHG) is effective in describing widget behaviors

Contribution Analysis of Different Design Choices

Explore the contributions of different design choices in UI-CTX

- Code Context pruning, API Summarization, and UHG Embedding

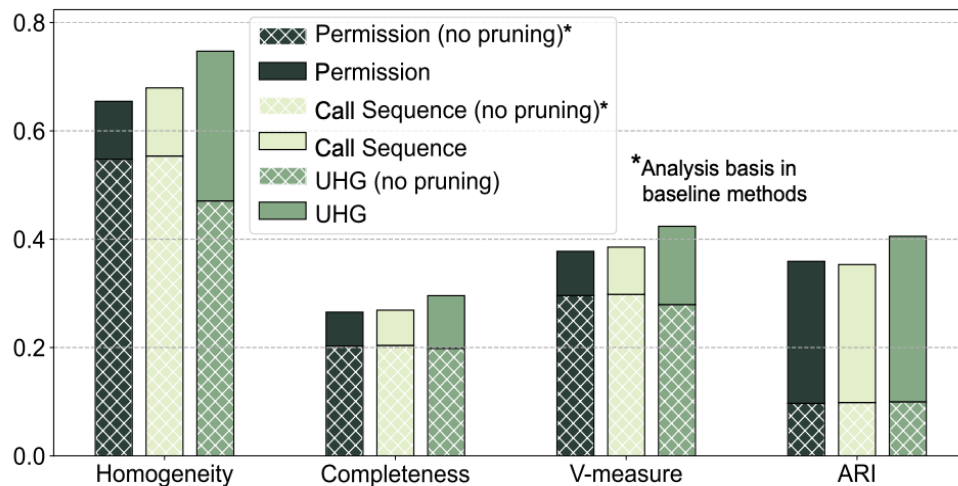


- Context pruning identifies accurate and concise code contexts

Contribution Analysis of Different Design Choices

Explore the contributions of different design choices in UI-CTX

- Code Context pruning, API Summarization, and UHG Embedding



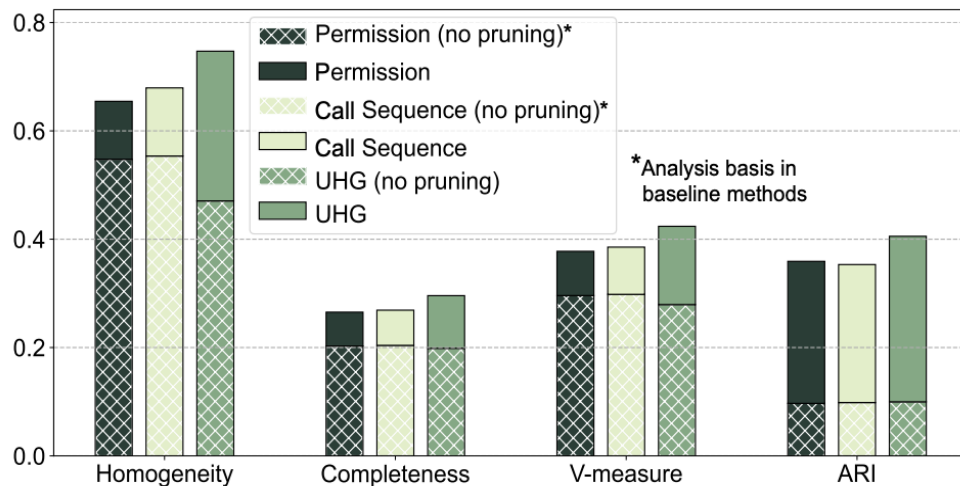
API hop	∞	6	5	4	3	2	1
% of Node	100	61.7	56.0	49.8	42.7	36.3	32.1
% of Edge	100	52.5	47.2	41.9	36.5	31.3	27.9
F1-score	0.76	0.77	0.78	0.79	0.79	0.80	0.81

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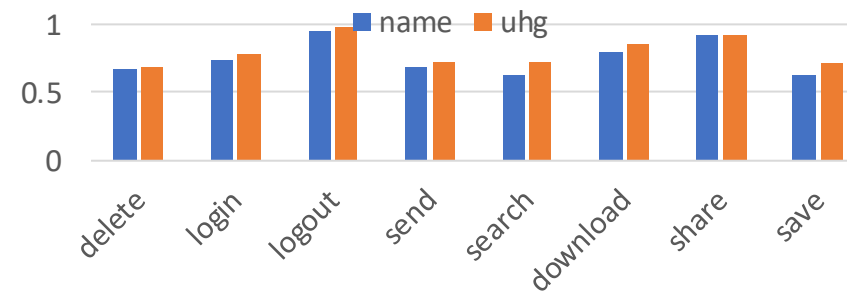
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- API Summarization reduces unnecessary external code
- Opcodes provide more stable and informative function semantics

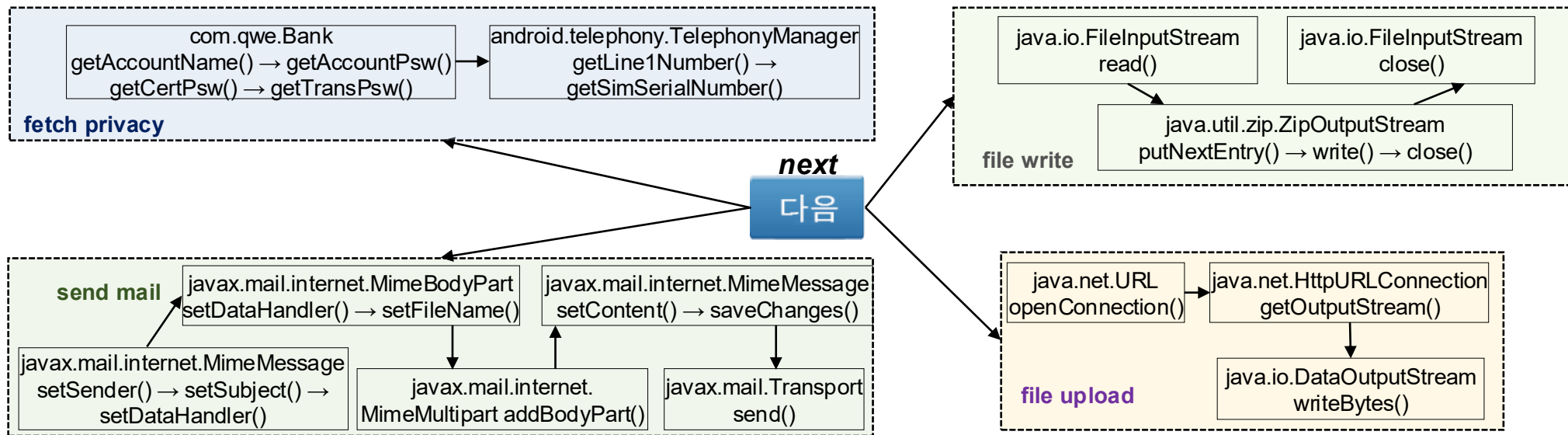
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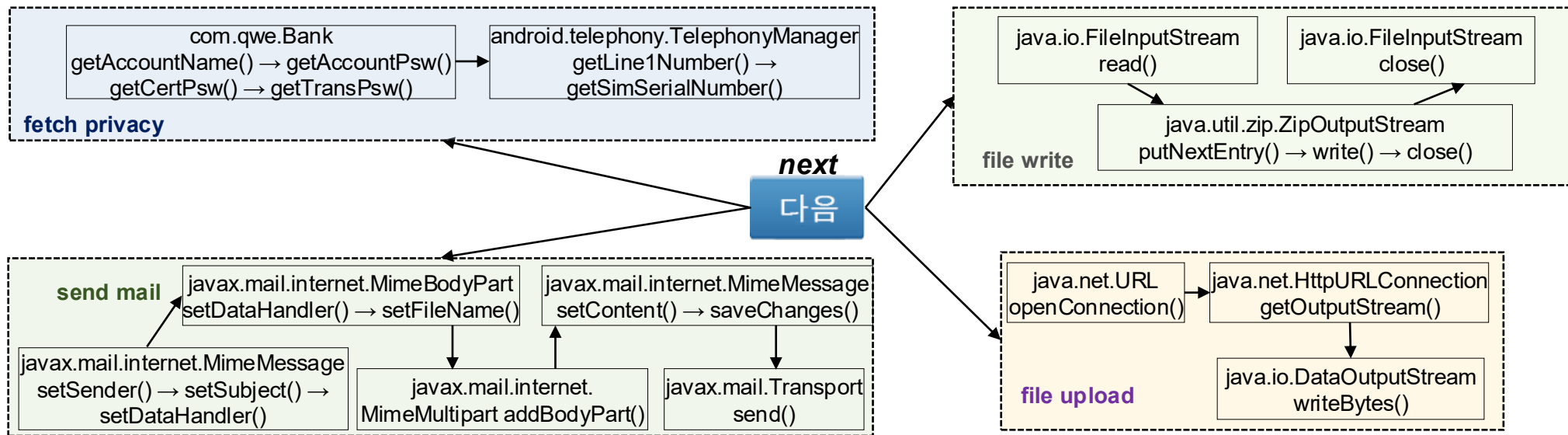
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UI-CTX can accurately present the malicious behavior behind the next button, facilitating security analysis

Summary

In this work, we:

- highlight the importance and identify the challenges of UI widget behavior representation, *e.g.*, identifying correct code contexts describing UI widget
- design UI Handler graph (UHG), a concise and accurate representation to describe UI widget behavior
- present UI-CTX, an end-to-end approach to build UHG, summarize and embed the semantics in UHG to investigate UI widget functionality



<https://github.com/DaweiX/UI-CTX>